Overview of Patents and Prior Art

- Asserted Patents
- Background
- Prior Art
- Specification
- Claims

The Asserted Patents

- U.S. Pat. No. 6,201,839: *Method and Apparatus for Correlation-Sensitive Adaptive Sequence Detection*
- U.S. Pat. No. 6,438,180: *Soft and Hard Sequence Detection in ISI Memory Channels*

(12) **United States Patent**
Kavcic et al.
(10) **Patent No.: US 6,201,839 B1**
(45) **Date of Patent: Mar. 13, 2001**

(54) **METHOD AND APPARATUS FOR CORRELATION-SENSITIVE ADAPTIVE SEQUENCE DETECTION**

(75) Inventors: **Aleksandar Kavcic; Jose M. F. Moura**, both of Pittsburgh, PA (US)

(73) Assignee: **Carnegie Mellon University**, Pittsburgh, PA (US)

(*) Notice:

(21) Appl. No.

(22) Filed:

Re

(60) Provisional 1997.

(51) **Int. Cl.**[7]
(52) **U.S. Cl.**
(58) **Field of S**

(56)

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5,689,532 *
5,737,342 *
5,781,590 *
5,784,415 *
5,844,946 *
5,856,983 *
5,862,192 *
5,914,988 *
5,920,599 *

5,937,020	*	8/1999	Hase et al.	375/376
5,970,091	*	10/1999	Nishida et al.	375/231
5,978,426	*	11/1999	Glover et al.	375/376

OTHER PUBLICATIONS

Nakagawa et al., "A Study on Detection Methods of NRZ Recording", IEEE Trans. On Magnetics, vol. MAG–16, No. 1, pp. 104–10, Jan. 1980.
Chevillat et al., "Noise–Predictive Partial–Response Equalizers and Applications," IEEE ICC '92 Conference Record,

(12) **United States Patent**
Kavcic et al.
(10) **Patent No.: US 6,438,180 B1**
(45) **Date of Patent: *Aug. 20, 2002**

(54) **SOFT AND HARD SEQUENCE DETECTION IN ISI MEMORY CHANNELS**

(75) Inventors: **Aleksandar Kavcic**, Cambridge, MA (US); **Jose M. F. Moura**, Pittsburgh, PA (US)

(73) Assignee: **Carnegie Mellon University**, Pittsburgh, PA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

This patent is subject to a terminal disclaimer.

(21) Appl. No.: **09/259,195**

(22) Filed: **Mar. 1, 1999**

Related U.S. Application Data

(63) Continuation-in-part of application No. 09/055,003, filed on Apr. 3, 1998.
(60) Provisional application No. 60/046,006, filed on May 9, 1997.

(51) **Int. Cl.**[7] **H03D 1/00**
(52) **U.S. Cl.** **375/341**; 714/796
(58) **Field of Search** 375/262, 265, 375/285, 340, 341, 343, 348; 714/791, 792, 793–796, 716, 719, 722

(56) **References Cited**

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5,844,946 A		12/1998	Nagayasu	375/341
5,856,983 A		1/1999	Okazaki	371/21.4
5,862,192 A		1/1999	Huszar et al.	375/347
5,914,988 A		6/1999	Hu et al.	375/341
5,920,599 A		7/1999	Igarashi	375/341
5,937,020 A		8/1999	Hase et al.	375/376
5,970,091 A		10/1999	Nishida et al.	375/231
5,978,426 A		11/1999	Glover et al.	375/376
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6,201,839 B1	*	3/2001	Kavcic et al.	375/341
6,215,831 B1	*	4/2001	Nowack et al.	375/340

OTHER PUBLICATIONS

Nakagawa et al., "A Study on Detection Methods of NRZ Recording", IEEE Trans. On Magnetics, vol. MAG–16, No. 1, pp. 104–10, Jan. 1980.
Chevillat et al., "Noise–Predictive Partial–Response Equalizers and Applications," IEEE CC '92 Conference Record, pp. 942–947, Jun. 1992.

(List continued on next page.)

Primary Examiner—Chi Pham
Assistant Examiner—Bayard Emmanuel
(74) *Attorney, Agent, or Firm*—Kirkpatrick & Lockhart LLP

(57) **ABSTRACT**

A method of determining branch metric values in a detector. The method includes receiving a plurality of time variant signal samples, the signal samples having one of signal-dependent noise, correlated noise, and both signal dependent and correlated noise associated therewith. The method also includes selecting a branch metric function at a certain time index and applying the selected function to the signal samples to determine the metric values.

27 Claims, 12 Drawing Sheets

Sequence Detection Background

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention is directed generally to high[...] magnetic recording sequence detectors, [...] particularly, to correlation-sensitive seque[...]

2. Description of the Background

In recent years, there has bee[...] shift in th[...] of signal detectors in magnetic recording. Traditio[...] detectors (PD), such as those described in Nakagaw[...] "A Study of Detection Methods of NRZ Recording[...] Trans. Magn., vol. 16, pp. 1041–110, Jan. 1980, ha[...] replaced by Viterbi-like detectors in the form o[...] response maximum likelihood (PRML) schemes or [...] between tree/trellis detectors and decision feedbac[...] izers (DFE), such as FDTS/DF, MDFE and RA[...] These methods were derived under the assumption that additive white Gausian noise (AWGN) is present in the system. The resulting trellis/tree branch metrics are then computed as Euclidian distances.

It has long been observed that the noise in magnetic recording systems is neither white nor stationary. The nonstationarity of the media noise results from its signal dependent nature. Combating media noise and its signal dependence has thus far been confined to modifying the Euclidian branch metric to account for these effects. Zeng, et al., "Modified Viterbi Algorithm for Jitter-Dominated 1-D^2 Channel," IEEE Trans. Magn., Vol. MAG-28, pp. 2895–97, Sept. 1992, and Lee et al., "Performance Analysis of the Modified maximum Likelihood Sequence Detector in the Presence of Data-Dependent Noise," Proceedings 26th Asi[...] lomar Conference, pp. 961–64, Oct. 1992 h[...] branch metric computation method for combating the signal-dependent character of media noise. These references ignore the correlation between noise samples. The effectiveness of this method has been demonstrated on real data in Zayad et al., "Comparison of Equalization and Detection for Very High-Density Magnetic Recording," IEEE INTERMAG Conference, New Orleans, April 1997.

In recent years, there has been a major shift in the design of signal detectors in magnetic recording. Traditional peak detectors (PD), such as those described in Nakagawa et al., "A Study of Detection Methods of NRZ Recording", IEEE Trans. Magn., vol. 16, pp. 1041–110, Jan. 1980, have been replaced by Viterbi-like detectors in the form of partial response maximum likelihood (PRML) schemes or hybrids between tree/trellis detectors and decision feedback equalizers (DFE), such as FDTS/DF, MDFE and RAM-RSE. These methods were derived under the assumption that additive white Gausian noise (AWGN) is present in the system. The resulting trellis/tree branch metrics are then computed as Euclidian distances.

It has long been observed that the noise in magnetic recording systems is neither white nor stationary. The nonstationarity of the media noise results from its signal dependent nature. Combating media noise and its signal dependence has thus far been confined to modifying the Euclidian branch metric to account for these effects. Zeng, et al., "Modified Viterbi Algorithm for Jitter-Dominated 1-D^2 Channel," IEEE Trans. Magn., Vol. MAG-28, pp. 2895–97, Sept. 1992, and Lee et al., "Performance Analysis of the Modified maximum Likelihood Sequence Detector in the Presence of Data-Dependent Noise," Proceedings 26th Asilomar Conference, pp. 961–64, Oct. 1992 have derived a branch metric computation method for combating the signal-dependent character of media noise. These references ignore the correlation between noise samples. The effectiveness of this method has been demonstrated on real data in Zayad et al., "Comparison of Equalization and Detection for Very High-Density Magnetic Recording," IEEE INTERMAG Conference, New Orleans, April 1997.

'839 Patent col. 1

Background Detectors: Zeng (Univ. of Minn.)

Modified Viterbi Algorithm for a Jitter-dominant $1 - D^2$ Channel*

Weining Zeng and Jaekyun Moon
The Center for Micromagnetics and Information Technologies
Department of Electrical Engineering, University of Minnesota, Minneapolis, MN 55455

ABSTRACT

One way to improve data capacity in magnetic recording is to increase linear density by storing magnetic transitions more closely in each track. However, experiments have shown that one drawback of such practice is the substantial increase of transition noise. Transition noise will degrade the performance of the detector, and, thus, reduce reliability of the reproduced information. Random jitter in the transition position is believed to be one of the major contributions to transition noise. Transition noise cannot be modeled as additive noise since it is data-dependent. In this paper, we propose a new detection scheme which yields better performance than the conventional Viterbi detector in jitter-dominant recording channels. The proposed detection scheme is based on the Gaussian jitter assumption, and is very similar to the Viterbi algorithm (VA) except that a modified branch error metric is used to incorporate the data-dependent nature of jitter noise. Error rate simulation results, obtained for channels dominated by either Gaussian jitter or truncated Gaussian jitter, show that the proposed detection scheme yields lower error rates than the VA.

Equation (4) can be written in the vector form:

$$\vec{Z} = \vec{y} + \vec{n} \tag{5}$$

where the size of the vector is N. According to the maximum likelihood (ML) criterion, we need to find a particular $\vec{y}$ such that $\Pr(\vec{Z}|\vec{y})$ is maximized over all possible data patterns $\vec{y}$. Assuming $\vec{n}$ is Gaussian, $\Pr(\vec{Z}|\vec{y})$ can be expressed as

$$\Pr(\vec{Z}|\vec{y}) = \frac{1}{\sqrt{(2\pi)^N |V|}} \exp(-\frac{1}{2}(\vec{Z}-\vec{y})'\, V^{-1}(\vec{Z}-\vec{y})) \tag{6}$$

where V is the covariance matrix of $\vec{n}$ (assuming V is non-singular). Let e_k and λ_k be the normalized eigenvectors and eigenvalues of V, respectively, i.e.,

be computed easily without time delay. With this approximation, we obtain $\lambda_k = \sigma_k^2$ (the variance of n_k), and $q_k = Z_k - y_k$. Now the detection problem reduces to recursively minimizing $\sum_{k=1}^{N} (\ln \sigma_k^2 + (Z_k - y_k)^2/\sigma_k^2)$. This leads to our proposed detection scheme which has the same structure as the VA except that the error metric is given by $\ln \sigma_k^2 + (Z_k - y_k)^2/\sigma_k^2$ rather than $(Z_k - y_k)^2$, the standard error metric for the VA.

To implement the proposed algorithm, which we call the modified Viterbi algorithm (MVA), an extra effort is needed to compute the data-dependent noise power σ_k^2. For the $1 - D^2$ channel model, σ_k^2 is given by $4(a_k^2 + a_{k-1}^2)\sigma_\Delta^2 + \sigma_w^2$, where σ_Δ^2 and σ_w^2 are the variances of Δ_k and w_k, respectively. For any given state-to-state transition in the Viterbi trellis, a_k and a_{k-1} are known and we can compute σ_k^2 at any bit interval provided that σ_Δ^2 and σ_w^2 are given a priori. The next section discusses results from the error rate simulations for both MVA and VA.

Zeng and Moon, IEEE Trans. Magn. 2895 (1992)
(Marvell Exh. 10)

Background Detectors: Lee (Stanford Univ.)

Perfomance Analysis of the Modified Maximum Likelihood Sequence Detector in the Presence of Data-dependent Noise

Inkyu Lee* and John M. Cioffi

Information Systems Laboratory
Stanford University
Stanford, CA 94305-4055

1 Introduction

It has been recognized by many researchers [1, 2] that the transition–dependent noise in thin–film media becomes dominant as recording density increases. Non–stationary noise characteristics may significantly degrade the performance of the receivers designed for stationary AWGN channel.

There are two main sources of data–dependent media noise. The first is non–deterministic transition shift. At the boundary of transition, inter–reaction of the magnetic material causes transition shift, depending on write patterns. The second is pulse amplitude fluctuation, caused by fluctuation of transition width with data pattern.

In this paper, we have developed a method to cope with data–dependent noise. First, we present a modified maximum likelihood sequence detector that is optimal but impractical. We then modify this detector to a simpler error metric without significant loss of performance. Then, we compute the error rate of the proposed error metric using a *Chi–square* distribution. The error rate plots with various values for jitter noise term show that a small error–rate reduction can be made for class-IV partial response channel model.

Assuming the noise sequence $\mathbf{n}$ has a Gaussian distribution, the probability density function is

$$P_{\mathbf{z}|\mathbf{y}}(z|y) = P_{\mathbf{n}}(z-y)$$

$$= \frac{1}{\sqrt{(2\pi)^N \det R}} \exp\left(-\frac{(\mathbf{z}-\mathbf{y})^T R^{-1}(\mathbf{z}-\mathbf{y})}{2}\right) \quad (2)$$

where R is the covariance matrix of noise $\mathbf{n}$.

(still noise variance is varying over the samples). This simplification leads to a diagonal matrix R. Then the eigenvalues λ_k of R are equivalent to the noise power σ_k^2 at each sampling time $t = kT$. Now we can rewrite the new error metric (4) as

$$\sum_{k=1}^{M}\left(\log \sigma_k^2 + \frac{n_k^2}{\sigma_k^2}\right) \quad (5)$$

where $n_k = z_k - y_k$

I. Lee & J.M. Cioffi, Proc. 26th Asilomar Conference 961 (1992), Marvell Exh. 9

Background Detectors: Fitzpatrick (Quantum Corp.)

United States Patent [19]

Fitzpatrick

[11] **Patent Number: 5,689,532**

[45] **Date of Patent: *Nov. 18, 1997**

[54] **REDUCED COMPLEXITY EPR4 POST-PROCESSOR FOR SAMPLED DATA DETECTION**

[75] Inventor: **Kelly K. Fitzpatrick**, Mountain View, Calif.

[73] Assignee: **Quantum Corporation**, Milpitas, Calif.

[*] Notice: The term of this patent shall not extend beyond the expiration date of Pat. No. 5,521,945.

[21] Appl. No.: **655,358**

[22] Filed: **May 24, 1996**

Related U.S. Application Data

[63] Continuation of Ser. No. 497,520, Jun. 30, 1995, 5,521,945.

Wood, "Turbo–PRML: A Compromise EPRML Detector", *IEEE Transactions of Magnetics*, vol. 29, No. 6, Nov. 1993.

Forney, "The Viterbi Algorithm", *Proceeding, of the IEEE*, vol. 61, No. 3, Mar. 1973, pp. 268–2278.

Forney, "Maximum–Liklihood Sequence Estimation of Digital Sequence in the Presence of Inteersymbol Interfer-enc", *IEEE Transactions on Information Theory*, vol. IT–18, No. 3, May 1972.

Wood and Peterson, "Viterbi Detection of Class IV Partial Response on a Magnetic Recording Channel", IEEE Trans.

[57] **ABSTRACT**

An EPR4 detector comprises a PR4 Viterbi detector and an EPR4 post-processor for improving estimated output sequence at an output of the PR4 Viterbi. The PR4 Viterbi detector produces digital estimates of coded digital information values into the channel in accordance with a path through a PR4 trellis and produces other path information relating to other paths through the PR4 trellis. The EPR4

U.S. Pat. No. 5,689,532, Proakis Exh. 7 (Dkt. 84-8)

Background Detectors: Fitzpatrick (Quantum Corp.)

United States Patent [19] [11] **Patent Number: 5,689,532**

Fitzpatrick [45] **Date of Patent: *Nov. 18, 1997**

Another implementation approach is to use a PR4 Viterbi detector, followed by a post-processor for EPR4. A post-processor for an EPR4 channel that achieves nearly maximum-likelihood performance was described by Wood, "Turbo PRML: A Compromise EPRML Detector", *IEEE Trans. on Magnetics*, Vol. 29, No. 6, Nov. 1993, pp. 4018–4020. In the Turbo PRML post-processor technique, PR4 equalized samples are sent to a PR4 Viterbi detector that produces a preliminary estimate of the binary input sequence. Then, the preliminary estimate is sent to the post-processor to produce a final improved estimate of the binary input sequence.

3:29-40

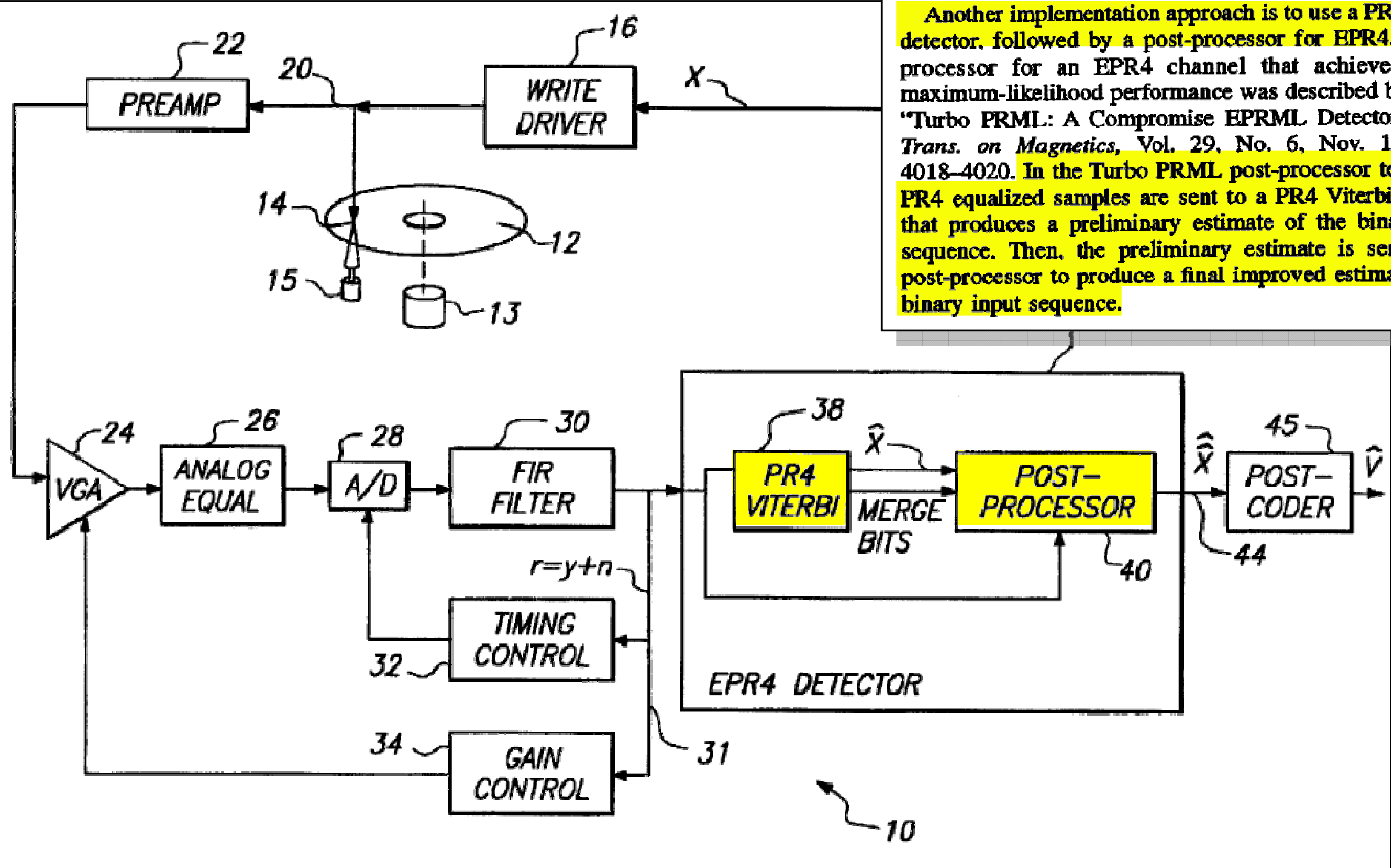


FIG. 5

Background Detectors: Fitzpatrick (Quantum Corp.)

United States Patent [19]	[11] Patent Number:	5,689,532
Fitzpatrick	[45] Date of Patent:	*Nov. 18, 1997

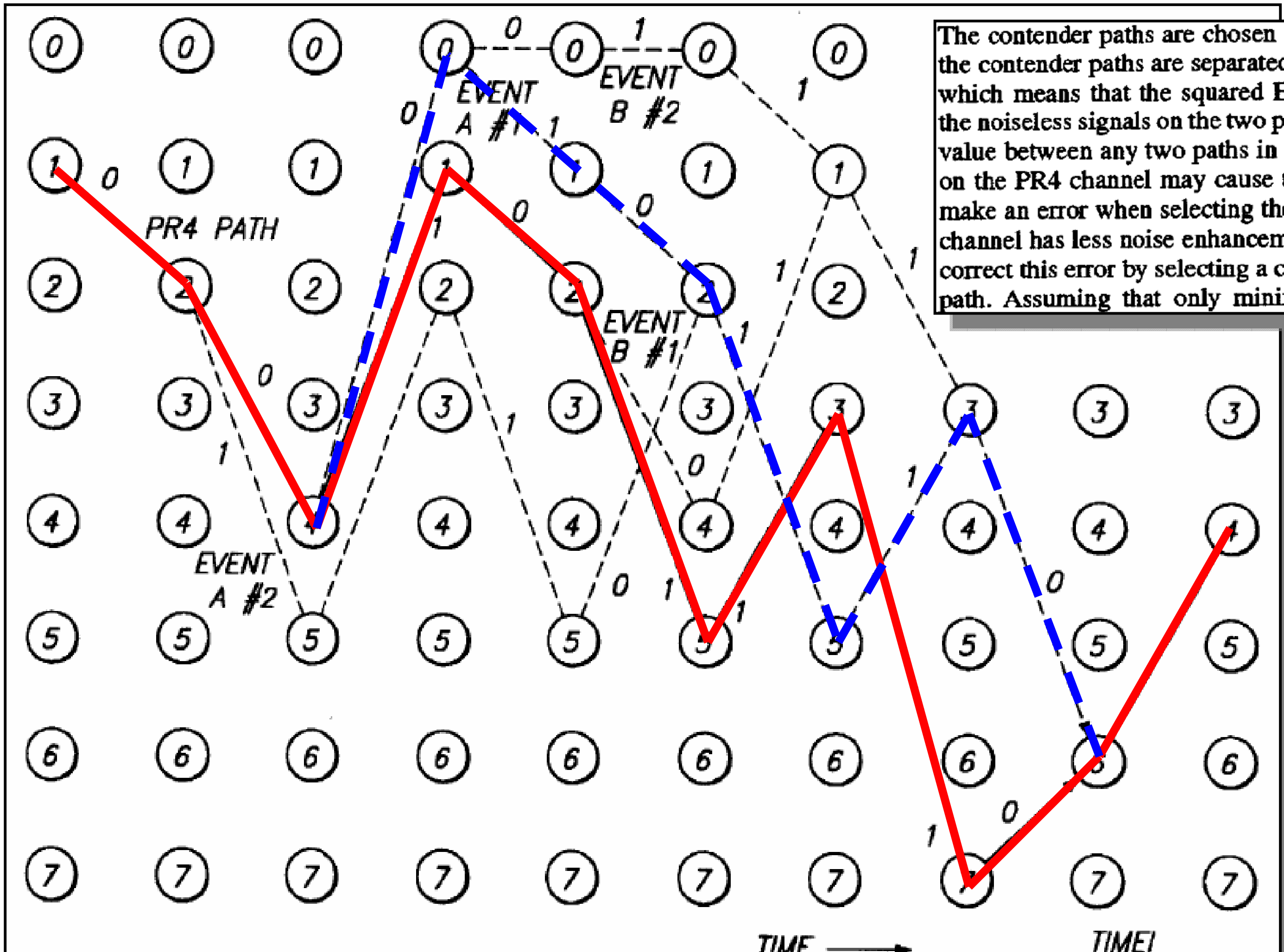


FIG. 7

The contender paths are chosen such that the PR4 path and the contender paths are separated by the minimum distance, which means that the squared Euclidean distance between the noiseless signals on the two paths is the smallest possible value between any two paths in the EPR4 trellis. The noise on the PR4 channel may cause the PR4 Viterbi detector to make an error when selecting the PR4 path. Since an EPR4 channel has less noise enhancement, the post-processor can correct this error by selecting a contender path over the PR4 path. Assuming that only minimum distance error-events

3:56-65

Background Detectors: Huszar (Lucent)

United States Patent [19]
Huszar et al.

[11] **Patent Number: 5,862,192**
[45] **Date of Patent: Jan. 19, 1999**

[54] **METHODS AND APPARATUS FOR EQUALIZATION AND DECODING OF DIGITAL COMMUNICATIONS CHANNELS USING ANTENNA DIVERSITY**

[75] Inventors: **Stephen Russell Huszar**, Bridgewater; **Nambirajan Seshadri**, Chatham, both of N.J.

[73] Assignee: **Lucent Technologies Inc.**, Murray Hill, N.J.

5,005,188	4/1991	Clark	375/341
5,056,117	10/1991	Gitlin et al.	198/725
5,081,651	1/1992	Kubo	375/341
5,164,961	11/1992	Gudmundson	375/341
5,191,598	3/1993	Bäckström et al.	375/347
5,195,107	3/1993	Wei	375/341
5,257,272	10/1993	Fredrickson	371/43.4
5,263,033	11/1993	Seshadri	371/43.4
5,263,053	11/1993	Wan et al.	375/341
5,272,727	12/1993	Okanoue	375/341
5,481,572	1/1996	Sköld et al.	375/347
5,499,272	3/1996	Bottomley	375/347

While the prior art adaptive Viterbi Algorithm uses the globally best estimates of the transmitted data to update the estimates of the channel impulse response, processing used to develop these estimates necessarily introduces considerable complexity and delay. In a rapidly changing channel environment, the channel estimates so obtained may no longer be sufficiently accurate for currently processed symbols.

2:15-22

U.S. Pat. No. 5,862,192 [Marvell Tutorial Exh. 6]

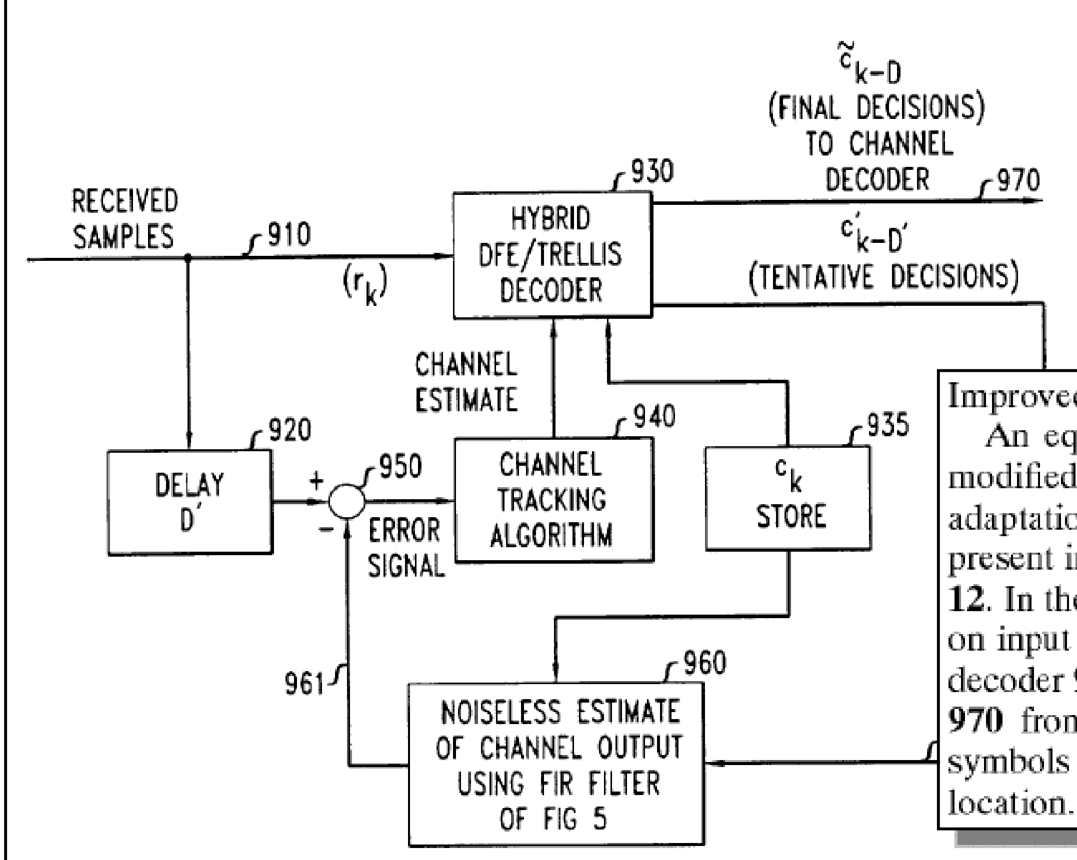
Background Detectors: Huszar (Lucent)

United States Patent [19] — **Huszar et al.**

[11] **Patent Number: 5,862,192**

[45] **Date of Patent: Jan. 19, 1999**

FIG. 12



Improved Equalizer/Decoder

An equalizer/decoder including an implementation of a modified (hybrid) Viterbi algorithm and enhanced channel adaptation algorithm in accordance with aspects of the present invention is shown in functional block form in FIG. **12**. In the arrangement of FIG. **12**, incoming samples arrive on input **910** where they are processed by the hybrid trellis decoder **930** in a manner detailed below. The outputs on lead **970** from decoder **930** are the final decisions as to what symbols C_k were sent from the modulator at the transmitting location.

10:41-51

Background Detectors: Huszar (Lucent)

United States Patent [19]   [11] **Patent Number: 5,862,192**

Huszar et al.   [45] **Date of Patent: Jan. 19, 1999**

FIG. 9

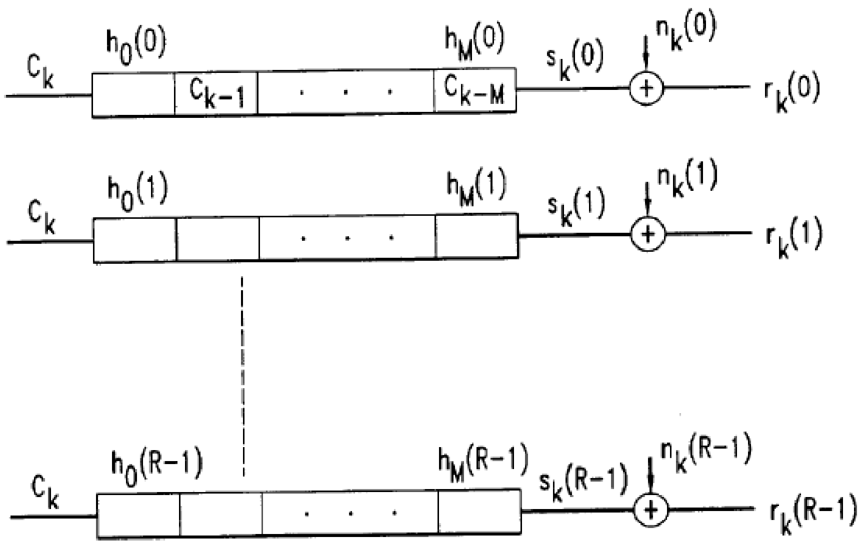


FIG. **9** shows a representation of an overall channel including R subchannels in accordance with the method described above. At each instant, the input to a subchannel is the data symbol c_k. The output of subchannel l is $r_k(l)$, l=0, 1, 2,–(R–1).

8:23-27

The two sampled outputs of the illustrative channel during the K^{th} time interval in absence of noise are given by

$$s_k(0) = \sum_{i=0}^{2} c_{k-i} h_i(0), \tag{16}$$

and

$$s_k(1) = \sum_{i=0}^{2} c_{k-i} h_i(1).$$

The problem of decoding then resolves to finding modulator output sequence $c=(c_{-n}, \ldots, c_{-1}, c_0, c_1, \ldots, c_n \ldots)$ such that the overall metric, J, where

$$J = \sum_{k=-\infty}^{+\infty} \|s_k(0) - r_k(0)\|^2 + \|s_k(1) - r_k(1)\|^2 \tag{17}$$

is minimized.

8:43-62

Background Detectors: Worstell (Seagate)

(12) **United States Patent**
Worstell

(10) **Patent No.: US 6,282,251 B1**
(45) **Date of Patent: Aug. 28, 2001**

(54) **MODIFIED VITERBI DETECTOR WHICH ACCOUNTS FOR CORRELATED NOISE**

(75) Inventor: **Glen Douglas Worstell**, Santa Cruz, CA (US)

(73) Assignee: **Seagate Technology LLC**, Shakopee, MN (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **08/407,230**

(22) Filed: **Mar. 21, 1995**

M. Kobayashi et al., "Beyond 1 um^2/bit High Density Recording with Improved QAM Technique," *IEEE Transactions on Consumer Electronics*, vol. 37, No. 3, pp. 283–290, Aug. 1991.
Kelly J. Knudson, Jack K. Wolf and Laurence V. Milstein, "Dynamic Threshold Implementation of the Maximum–Likelihood Detector for the EPR4 Channel", *Proceedings of Globecom 91, IEEE Communications Society*, pp. 2135–2139, Dec. 1991.
Robert W. Hawley, Thu–ji Lin and Henry Samueli, "A 300 MHz Digital Double–Sideband to Single–Sideband Converter in 1 μm CMOS", *IEEE Journal of Solid–State Circuits*, vol. 30, No. 1, pp. 4–10, Jan. 1995.

SUMMARY OF THE INVENTION

The present invention uses a branch metric in a Viterbi detector which is based on a current signal sample, as well as one or more previous signal samples. In this way, the Viterbi detector according to the present invention accounts for correlated noise in the system.

U.S. Patent No. 6,282,251, Marvell Exh. 12

Background Detectors: Worstell (Seagate)

(12) **United States Patent** (10) **Patent No.: US 6,282,251 B1**

Worstell (45) **Date of Patent: Aug. 28, 2001**

Knowing that noise in the present system is colored, and knowing that the noise samples are not independent, and now knowing the transfer function of FIR filter **22**, the noise autocorrelation at the input Viterbi detector **24** can be described. The present invention utilizes this information to modify the branch metric used in Viterbi detector **24**.

8:32-37

Rewritten in the same terms as the conventional branch metric set out Equations 1 and 2 above, the new branch metric of Equation 19 can be described as follows:

$$B_{b,nt} = X_{b,nt}^2 - 2X_{b,nt}\sum_{i=1}^{L} X_{b,(n-i)t}W_i \qquad \text{Equation 20}$$

where $B_{b,nt}$ is the branch metric for branch b at time nt;

$X_{b,nt}$ is the noise and equalization error at time nt for branch b;

W_i is the ith tap weight of FIR filter **22**;

L is the number of tap weights beyond the center weight.

9:45-58

The modified metric used in accordance with the present invention can be further modified to take into account transition noise as well. If it is assumed that the standard deviation of the noise component of each sample is greater where there is a transition in the signal written to the disc than where there is no transition, then each branch metric can be modified by multiplying the metrics which correspond to transitions by a fraction which depends on the transition noise standard deviation. Implementing this in a

10:53-56

Sequence Detector Timeline

March 1995
US Pat. No. 6,282,251 "*Modified Viterbi Detector Which Accounts for Correlated Noise*"
(Worstell/Seagate) (Exh. 12)

1992-1994:
Sequence Detection in the Presence of Media Noise
(Zeng/Univ. of Minn.)
(Exh. 10, 11)

1992:
Maximum Likelihood Sequence Detector for "Data-Dependent Noise"
(Lee/Stanford Univ.)
(Exh. 9)

1995:
Barbosa/UCSD IEEE "*A Model for Magnetic Recording Channels with Signal Dependent Noise*"; SPIE "*Towards the Detection of Signals in Presence of Signal-Dependent Noise*"
(Exh. 13, 14)

June 1996
Eleftheriou/IBM "*Noise-Predictive Maximum-Likelihood (NPML) Detection for Magnetic Recording Channel*"

May 1997
CMU Provisional Patent Application filed

March 2001
CMU '839 Patent Issues;

Jan. 2002
Marvell files Prov. Patent App.
(US Pat. No. 6,931,585):
"*Detection in the Presence of Media Noise*"
(Exh. 20)

Aug. 2002
CMU '180 Patent Issues.

Aug. 2005
Marvell's '585 Patent issues over CMU Patents.

1990's **2000's**

April 1967:
Andrew J. Viterbi proposes Maximum Likelihood Decoder (Exh. 9)

1973:
Applications to Magnetic Recording are described by Forney (Exh. 10)

1980's:
Modifications of Viterbi Algorithm for Magnetic Recording
R.W. Wood & D.A. Petersen, *Viterbi Detection of Class IV Partial Response on a Magnetic Recording Channel*, IEEE Trans. Commun. 454 (1986) (Exh. 7)
H.K. Thapar & A.M. Patel, *A Class of Partial Response Systems for Increasing Storage Density in Magnetic Recording*, IEEE Trans. Magn. 3666 (1987) (Exh. 8)

[Exh. Nos. refer to exhibits attached to Marvell's Claim Construction Brief (Dkt. 82)]